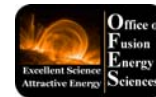


Supported by



# NSTX Research Plan – FY05-07

## Contributing to Fusion Energy Science, Burning Plasma (ITER), & Concept Optimization

Martin Peng  
ORNL

For the NSTX Team

Budget Planning Meeting – FY 2007

March 15-16, 2005  
Germantown, Maryland

RESEARCHERS: 150

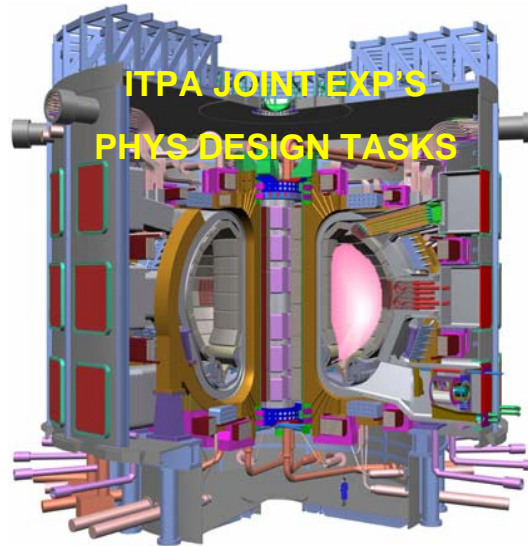
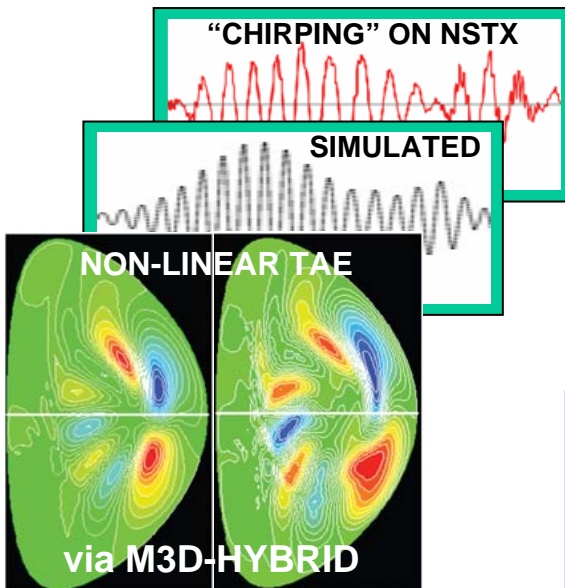
Columbia U  
Comp-X  
General Atomics  
INEL  
Johns Hopkins U  
LANL  
LLNL  
Lodestar  
MIT  
Nova Photonics  
New York U  
Old Dominion U  
ORNL  
PPPL  
PSI  
SNL  
UC Davis  
UC Irvine  
UCLA  
UCSD  
U Maryland  
U Rochester  
U Washington  
U Wisconsin  
Culham Sci Ctr  
Hiroshima U  
HIST  
Kyoto U  
Kyushu U  
Kyushu Tokai U  
NIFS  
Niigata U  
U Tokyo  
JAERI  
Ioffe Inst  
TRINITI  
KBSI  
KAIST  
ENEA, Frascati  
CEA, Cadarache  
IPP, Jülich  
IPP, Garching  
U Quebec

# NSTX Will Advance Toroidal Plasma Science, Burning Plasma Physics, and Configuration Optimization

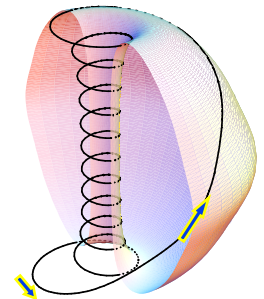


## Burning Plasma

### Science: Extended Parameters



### Optimization: Unique & Complementary



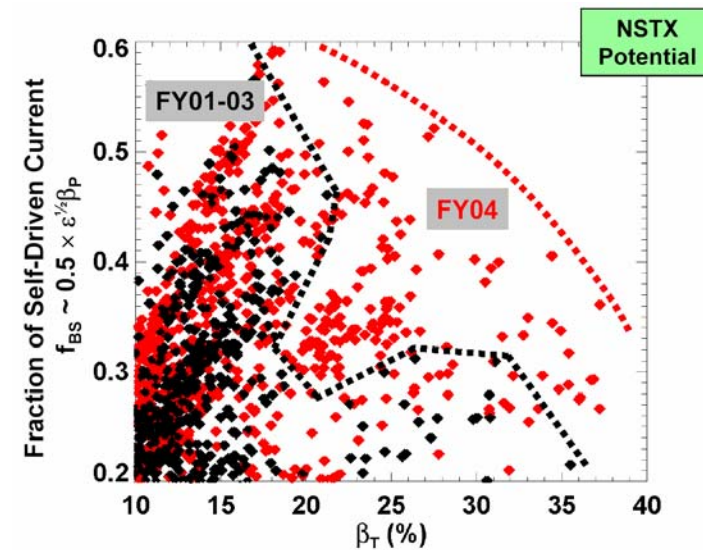
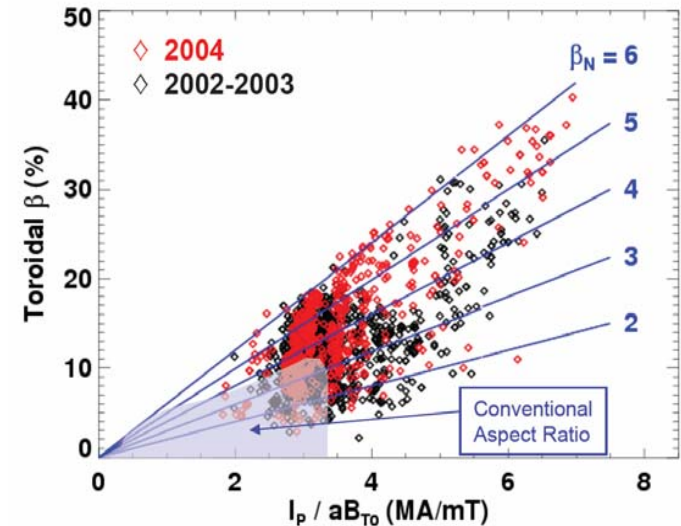
### Contribute to OFES Strategic Goals by Addressing Scientific Topics:

- Microturbulence & Transport
- Macroscopic Stability
- Waves & Energetic Particles
- Magnetic Flux Generation
- Boundary Interactions
- Synergy & Integrated Scenarios

# NSTX Had a Successful Year; Achieved 21 Run-Weeks; Made Key Progress on a Broad Scientific Front



- **Expanded parameter space** via improved control, shaping & operation – broadening plasma science.
- **Extended high beta-tau discharges with high B/S fraction** to  $> \tau_{\text{skin}}$ , with wall-stabilization of strongly rotating plasma.
- Measured RWM at substantially above no-wall limit, indicating  $\omega_{\text{crit}}/\omega_A \sim 1/q^2$ , consistent with neoclassical visc.
- Measured large radial correlation length of fluctuations in core that decreases with increasing  $B_T$  and radius.
- Observed increased electron energy confinement via reversed q-shear; verified ion Internal Transport Barrier.
- **Reconstructed equilibria for strong plasma rotation**, constrained by isothermal electrons and MSE field pitch.
- Determined via MSE & EFIT changes in core current density resulting from variations in operating scenario.
- **Observed and modeled \*AE's** driven by supra-Alfvénic ions, which are anticipated in ITER burning plasma.
- Measured via NPA fast ion depletion due to MHD modes.
- **Identified bursts of edge plasma filaments (“blobs”) as primary characteristics of ELMs** of varied severity.
- Measured EBW emission from core, consistent with theory.
- Obtained first evidence of parametric ion heating by HHFW.



# NSTX Prepared Three Plans for FY 2006-2007 to Deal with Present Uncertainties



Case	FY06 Rn-Wks	FY07 Rn-Wks	Accumulated	Upgrades
1	0	12	12	Minimal
2	12	12	24	Constrained
3	17	17	34	Optimized

- Case 2 in some detail
- Impact of Case 1
- Benefits of Case 3
- Summary charts of milestones as backup

*Requested FY07 information for 0, 6, 12, 20, & 25 run-weeks  
is supplied separately in hand-outs*



# Transport Studies Will Emphasize High-k Turbulence and Electron Transport, Leveraging Large $\beta$ , $\rho^*$ , q-Shear



## Motivation & NSTX Opportunities

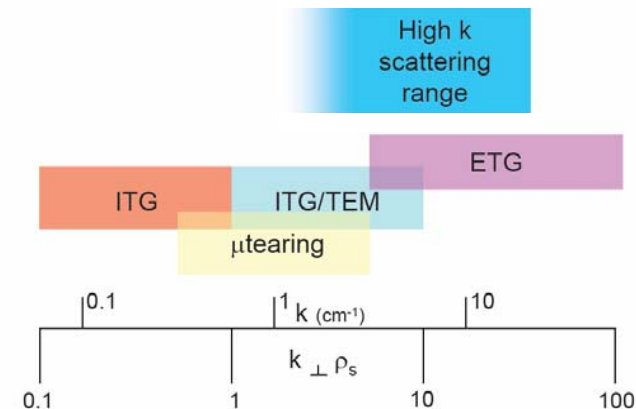
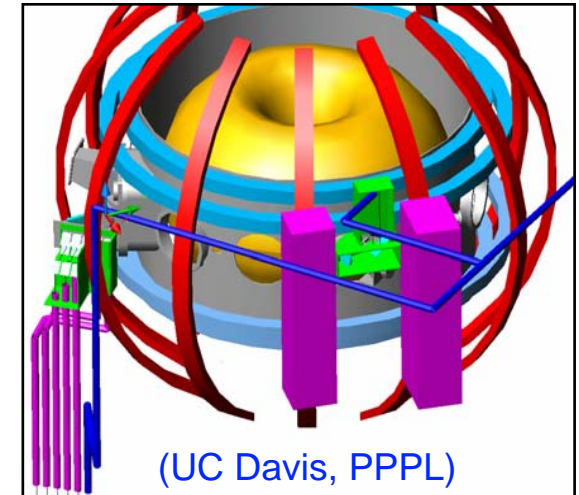
- Priority Panel (T4) & world priority; TTF initiative with emphasis on extended understanding of electron scale transport
- Key remaining scaling uncertainty for ITER – add to ITPA
- Large  $k$  ( $= 2 - 20 \text{ cm}^{-1}$ ), q-shear,  $\sim 3 \text{ cm}$  spatial resolution
- Central  $\beta$  up to unity  $\rightarrow$  clarify electromagnetic effects

## Milestones

- FY05: test high-k  $\mu\omega$  scattering; extend MSE;  $q'$  &  $\nabla T_e$  effects
- FY06: measure high-k turbulence in wide parameters
- FY07: correlate turbulence spectra with electron transport
- Extensive analysis: NL-GS2, GTC, FULL, GYRO, TRANSP

## Additional Investigations

- Strengthen ITPA global ELMy H-mode & pedestal database
- iITB similarity experiments, momentum transport, with MAST
- H-mode aspect ratio comparison with DIII-D



## 1) Transport & Turbulence: Physical processes that govern heat, particle & momentum confinement

Characterize  $q'$  &  $\nabla T_e$  effects  
on electron transport

Measure high-k  
turbulence

Assess high-k turbulence  
spectra and electron transport

FY05 (17 wks)

FY06 (12 wks)

FY07 (12 wks)

# Macroscopic Stability Studies to Advance Physics of Pressure-Limiting Modes via Feedback & Strong Shaping



## Motivation & NSTX Opportunities

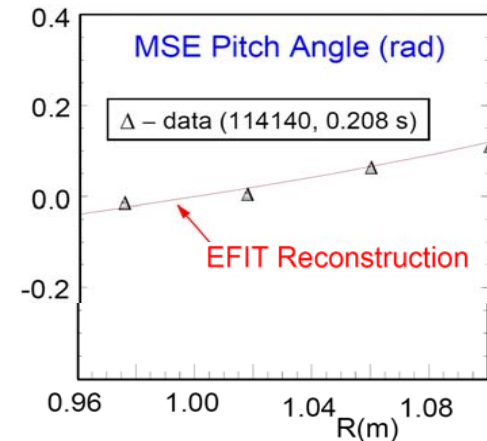
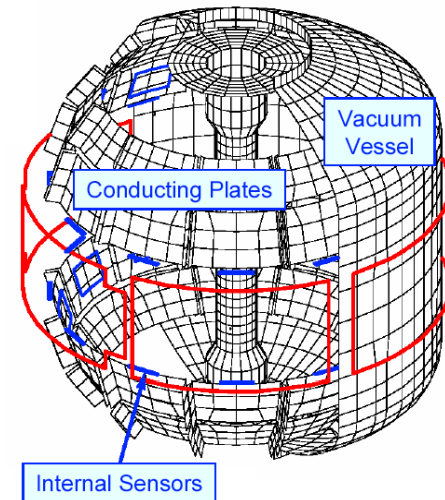
- Priority Panel (T2): what limits maximum pressure that can be achieved in laboratory plasmas? Also to enhance ITER performance
- Improved shaping ( $\kappa \leq 2.7$ ,  $\delta \leq 0.9$ )  $\Rightarrow \beta_T \leq 40\%$ ,  $\beta_N \leq 6$ ,  $I_N \leq 6.5$ , low  $\ell_i$
- New ex-vessel control coils, SPA power, internal sensors, with feedback capabilities progressively phased-in
- Resolve mode dynamics via  $\beta_0 \rightarrow 1$ ,  $V_\phi \rightarrow V_{\text{Sound}} \rightarrow V_{\text{Alfvén}}$ ,  $V_\phi' \rightarrow \gamma_{\text{MHD}}$

## Milestones

- FY05: explore high- $\beta$  plasmas via minimizing EF
- FY06: correlate resonant error field amplification, locked mode,  $\beta$
- FY07: explore very high  $\beta$  regime close to wall-stabilized limit!
- Extensive analysis: EFIT- $V_\phi$ -isotherm-MSE, VALEN, MARS, M3D, ...

## Additional Investigations

- Joint experiments on RWM & locked mode physics with Tokamaks
- Aspect ratio comparison on NTM physics with Tokamaks



## 2) Macroscopic Stability: Role of magnetic structure on plasma pressure & bootstrap current

Study rotating plasmas close to “wall-stability” with EF correction

Characterize effectiveness of closed-loop EF/LM control

Characterize effectiveness of closed-loop RWM control

FY05 (17 wks)

FY06 (12 wks)

FY07 (12 wks)

# Wave-Particle Research Will Make Unique Contributions to Understanding Supra-Alfvénic Ion Driven Modes for ITER



## Motivation & NSTX Opportunities

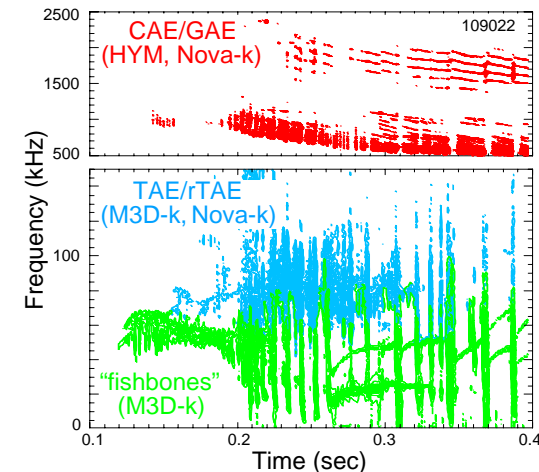
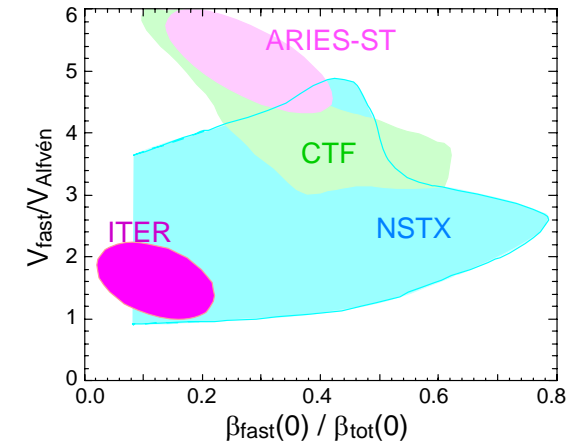
- ITER burning plasma will have supra-Alfvénic  $\alpha$ 's & beam ions
- NSTX covers the ITER regime in  $V_{\text{fast}}/V_A$  and  $\beta_{\text{fast}}/\beta_T$ ; and has measured range of \*AE's driven by such ions of confined orbits

## Milestones

- FY05: measure \*AE's & correlate with fast ion,  $J_{\text{NB}}$  changes
- Extensive core measurements: USXR tomography for mode structure; fast tang. interferometer for amplitude; MSE for J profile
- Extensive analysis: linear & non-linear simulations
- Future: understand fast ion transport due to \*AE cascades
- FY06: understand edge coupling (parametric and RF sheath effects) and optimize HHFW scenario

## Additional Investigations

- EBW: B-X-O emission @ 20-40 GHz, to understand potential of Ohkawa current drive & electron phase space science
- Accumulate physics database for future high power EBW



## 3) Wave-Particle Interaction: Use of electromagnetic waves to sustain and control high-temperature plasmas

Assess effects of supra-Alfvénic ion driven instabilities on core  $J_{\text{NB}}$

Characterize & optimize HHFW coupling

FY05 (17 wks)

FY06 (12 wks)

FY07 (12 wks)

# Solenoid-Free Start-up Tests Will Contribute to Understanding of Flux Generation and Reconnection



## Motivation & NSTX Opportunities

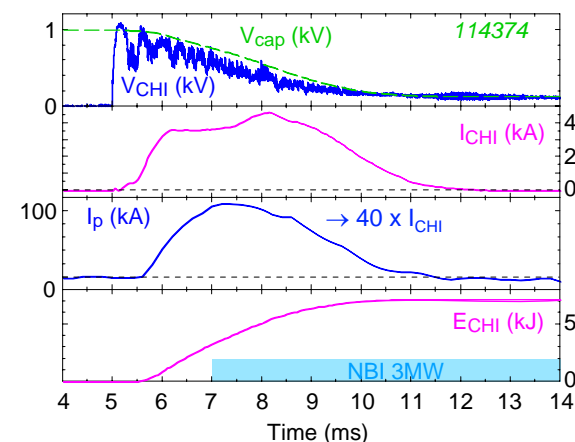
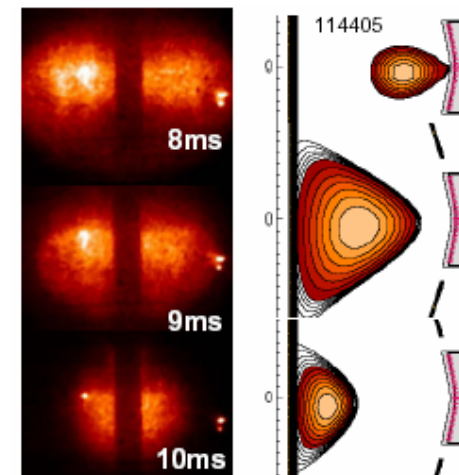
- Priority Panel (T6); important to tokamak reactor attractiveness; required for compact ST such as CTF
- Low A  $\rightarrow$  low internal magnetic flux and helicity
- Large progress: **HIT-II** (CHI to 200 kA); **TST-2, LATE** (ECH + VF to  $0.1 I_{TF} \sim 10$  kA); **JT-60U** (ECH + VF, to  $>100$  kA for  $>100$  ms); **MAST** (merging-compression, to 500 kA); **NSTX** (HHFW + field null, to 20 kA); **Pegasus** (e-beam, to 10 kA)

## Milestones

- FY06: test & understand conditions and scenarios for flux closure via CHI injector gas puff, 2-kV, low- $I_p$  control
- FY07: clarify low-A physics for NBI & HHFW current ramp-up
- Extensive analysis: TSC, EFIT- $J_{SOL}$ , LRDIAG, DINA

## Additional investigations

- Extend HHFW initiation with ECH preionization
- Collaborate with MAST; proposal to JET (LH-initiation)



## 4) Start-up, Ramp-up and Sustainment: Physical processes of magnetic flux generation and reconnection

Assess CHI creation of closed magnetic flux

Test solenoid-free ramp-up

FY05 (17 wks)

FY06 (12 wks)

FY07 (12 wks)



# Boundary Physics Studies Aim to Understand Pedestal-SOL Science of Long-Pulse High-P/R Plasmas



## Motivation & NSTX Opportunities

- Priority Panel (T10); enhance progress to predict H-mode pedestal with high confidence; ITPA priority
- Low A:  $B_p/B_T \sim 1$ , large  $B_{in}/B_{out}$  &  $\rho^*$ , P/R  $\rightarrow 15$  MW/m
- New tools: Li pellets/coating, supersonic gas jet, better TS

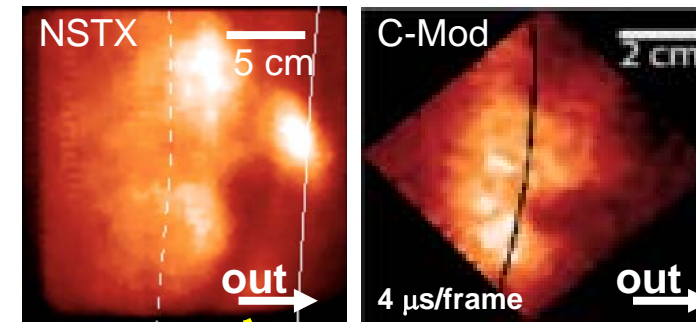
## Milestones

- FY05: document detail of pedestal-SOL properties and dynamics
- Successful GPI adopted by several experiments
- “Blobs” linked to ELMs; “peeling” or shear Alfvén?
- FY07: document Li coating effects on recycling and core plasma; database for advanced particle control
- Extensive analysis: BOUT, ELITE, UEDGE, DEGAS2

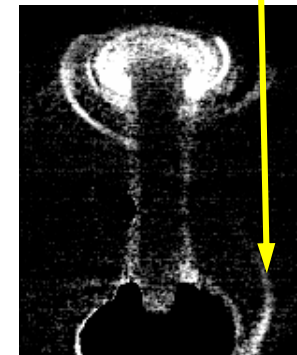
## Additional Investigations

- Pedestal similarity, small ELM comparison, “blob” characteristics comparison, with MAST, DIII-D, C-Mod

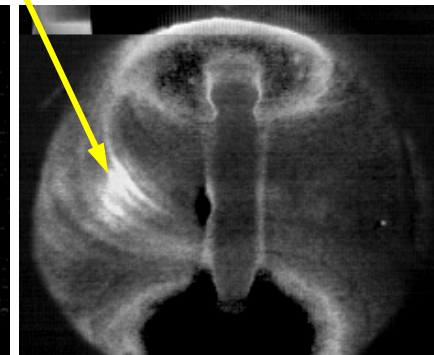
## Gas Puff Magnig (GPI)



## Small ELM



## Large ELM



## 5) Boundary Physics: Interface between fusion plasmas and normal temperature surroundings

Characterize pedestal and SOL of low-A, H-mode, high P/R plasmas

Characterize Li pellet & evaporator coating effectiveness

FY05 (17 wks)

FY06 (12 wks)

FY07 (12 wks)

# Integrated Scenario Studies Contribute to Understanding of Self-Organization and External Control



## • Motivation & NSTX Opportunities

- Priority Panel (T3): integrated understanding of self-organization & external control, enabling high-pressure sustained plasmas; ITER “hybrid” mode
- High  $\beta$  & low A: clarify B/S vs. CD
- Clarify future EBW and particle control needs

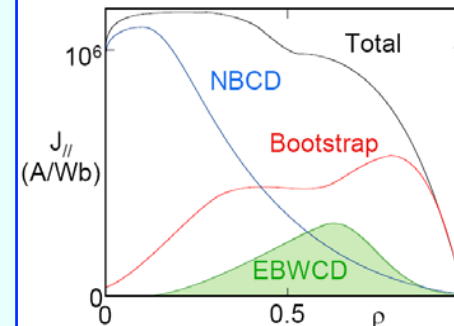
## • Milestones

- FY05: document and understand physics interplay of attractive, low- $V_L$ , NBI plasmas
- FY06: benchmark simulation models & codes
- Identify needed “actuators” & model improvements
- Future: determine conditions for surface  $V_L = 0$  long-pulse operation, though  $q_0$  may evolve

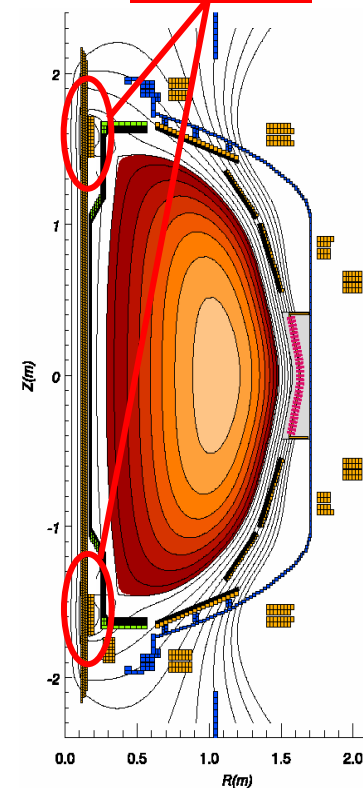
## • Additional Investigations

- Contribute to mapping of ITER/NSTX hybrid scenario, accounting for \*AE effects

$I_p = 1 \text{ MA}$   
 $\kappa = 2.7; \delta = 0.9$   
 $P_{\text{NBI}} = 4 \text{ MW}$   
 $P_{\text{HHFW}} = 3 \text{ MW}$   
 $P_{\text{EBW}} = 3 \text{ MW}$   
 $\langle n_e \rangle = 2.7 \times 10^{19} \text{ m}^{-3}$   
 $H_{98y2} = 1.5$   
 $\beta_T = 41\%; \beta_N = 8.9$   
 Stable  $n = 1, 2, 3 \text{ \& } \infty$



## High-Performance Sustained Plasma via New PF1A



## 6) Physics Integration: Synergistic effects of external control and self-organization

Characterize high-B/S &  
 low- $V_L$  plasmas for  $> \tau_{\text{skin}}$

Benchmark time-dependent  
 scenario simulation with data

FY05 (17 wks)

FY06 (12 wks)

FY07 (12 wks)

# NSTX Participates Strongly in ITPA Topical Groups and is Committed to Important 2005 Joint Experiments



Topical Groups	ID#	Burning Plasma Issues	Participating Programs
Confinement Database & Modeling	CDB-2	$\beta$ degradation in confinement scaling of ELMy H-modes	AUG, DIII-D, JET, JT-60U, MAST, NSTX, Tore-Supra
	CDB-6	Improving condition of global ELMy H-mode and pedestal database: low A	DIII-D, MAST, NSTX
Transport Physics	TP-8.1	ITB similarity experiments	MAST, NSTX
	TP-9	H-mode aspect ratio comparison	DIII-D, MAST, NSTX
Pedestal & Edge Physics	PEP-9	Pedestal similarity experiments	DIII-D, MAST, NSTX
	PEP-16	Small ELM regime comparison	C-Mod, MAST, NSTX
Divertor, SOL	DSOL-9	Carbon migration and deposition	AUG, DIII-D, JET, JT-60U, NSTX, TEXTOR
	DSOL-15	Comparison of edge "blob" characteristics	C-Mod, JT-60U, NSTX, TJ-II, Tore-Supra
MHD, Disruption Control	MDC-2	Resistive Wall Mode physics	AUG, DIII-D, JET, JT-60U, NSTX, TEXTOR
	MDC-4	Neoclassical Tearing Mode – A comparison	AUG, DIII-D, MAST, NSTX
	MDC-6	Error field physics comparison	C-Mod, DIII-D, JET, MAST NSTX, TEXTOR
	MDC-9	Fast-ion redistribution by *AE & cascade	AUG, DIII-D, JET, JT-60U, NSTX
Steady-State Op	SSO-2.1	Complete mapping of hybrid scenario	AUG, DIII-D, JET, JT-60U, NSTX

# Case-1 Impact Will Be Severe – National Research Team will Strive to Make Important Contributions



- FY06 milestones delayed to FY07 (12 run-weeks).
- Three code and tool benchmark milestones for FY06:
  - *Compare EF/LM/RWM data with models of stability conditions.*
  - *Compare fast ion driven mode data with non-linear simulation.*
  - *Benchmark time-dependent scenario simulation with high-B/S, low- $V_L$  data.*
- Hold results review early in FY06; analyze data; present and publish FY05 results, expected to be extensive and important.
- Carry out ITER Physics Design Tasks using appropriate expertise.
- Enhance collaboration with MAST, DIII-D, C-Mod, etc. in critical topical areas, utilizing remote experimental participation.
- Install diagnostics and facility improvements (minimal non-labor funds) to prepare for early FY07 run.
- Hold FY07 NSTX Research Forum in FY06.

# NSTX Case-3 Plan will Advance OFES Strategic Goals Effectively in Science, Burning Plasma, and Optimization



- Exciting NSTX science can be accelerated.
  - *Combine EF & RWM active feedback control earlier; perform intensive tearing mode studies.*
  - *Measure fast-ion transport due to fast-ion driven modes.*
  - *Accelerate Li coating milestone; assess long-pulse heat & particle control requirements of low-A, H-mode, high P/R plasmas.*
  - *Characterize surface  $V_L = 0$  plasmas for  $> \tau_{skin}$ .*
  - *Make decision on advanced particle control.*
- Can enhance participation in ITPA on critical topics.
- Rapid progress in science will be made in a broad front.
- Begin high-power EBW preparation, a key to advancing performance of high- $\beta$ , high-B/S, high-confinement plasmas.



# NSTX Will Advance Toroidal Plasma Science, Burning Plasma Physics, and Optimization



- Prepared three plans with progressive levels of research.
- Case-2 plan, assuming 12 run-weeks for FY06 and FY07, will
  - *Emphasize high-k turbulence and electron transport;*
  - *Advance physics of pressure-limiting modes via feedback & very strong shaping;*
  - *Make unique contributions to understanding supra-Alfvénic ion driven mode;*
  - *Contribute to understanding of magnetic flux generation and reconnection;*
  - *Understand pedestal-SOL science of long-pulse high-performance plasmas.*
- NSTX addresses key Priority Panel topics and participates strongly in ITPA 2005 Joint Experiments.
- Case-1 impact will be severe – National Team will strive to make important contributions.
- Case-3 will advance OFES Strategic Plan Effectively.

*Next talk addresses Facility, Diagnostics, Budget.*

# Case-1 Plan (No Run in FY06, 12 Run-Weeks in FY07)

## Research Milestones



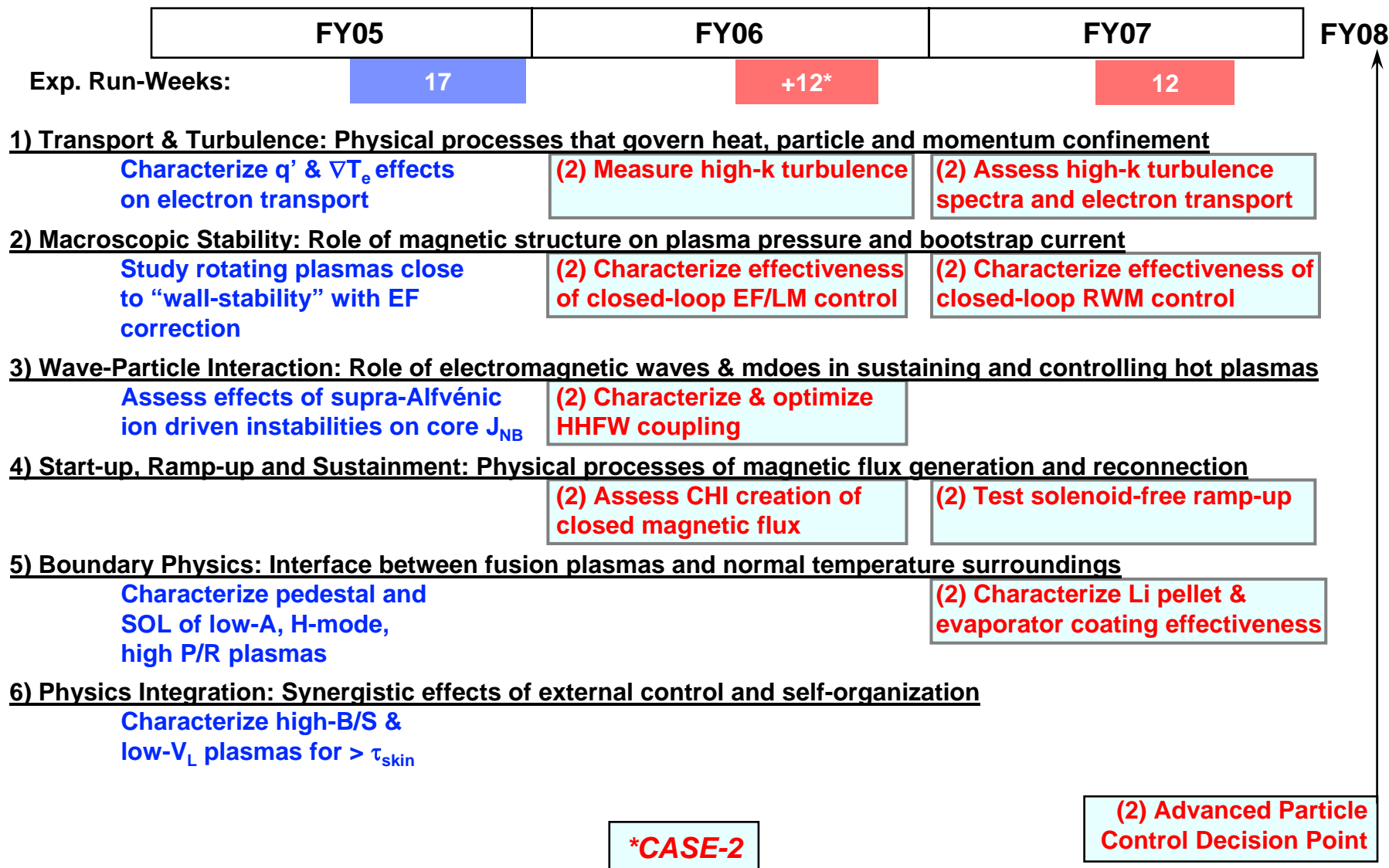
	FY05	FY06	FY07	FY09
Exp. Run-Weeks:	17	0*	12*	
<b>1) Transport &amp; Turbulence: Physical processes that govern heat, particle and momentum confinement</b>	Characterize $q'$ & $\nabla T_e$ effects on electron transport		(1) Measure high-k turbulence	
<b>2) Macroscopic Stability: Role of magnetic structure on plasma pressure and bootstrap current</b>	Study rotating plasmas close to "wall-stability" with EF correction	(1) Compare EF/RWM/LM data with theoretical models of stability conditions	(1) Characterize effectiveness of closed-loop EF/LM control	
<b>3) Wave-Particle Interaction: Role of electromagnetic waves &amp; modes in sustaining and controlling hot plasmas</b>	Assess effects of supra-Alfvénic ion driven instabilities on core $J_{NB}$	(1) Compare fast ion driven mode data with non-linear simulation	(1) Characterize & optimize HHFW coupling	
<b>4) Start-up, Ramp-up and Sustainment: Physical processes of magnetic flux generation and reconnection</b>			(1) Assess CHI creation of closed magnetic flux	
<b>5) Boundary Physics: Interface between fusion plasmas and normal temperature surroundings</b>	Characterize pedestal and SOL of low-A, H-mode, high P/R plasmas			
<b>6) Physics Integration: Synergistic effects of external control and self-organization</b>	Characterize high-B/S & low- $V_L$ plasmas for $> \tau_{skin}$	(1) Benchmark time-dependent scenario simulation with high-B/S & low- $V_L$ data		

**\*CASE-1**

**Advanced Particle Control Decision Point**

# Case-2 Plan (12 Run-Weeks for FY06 & FY07)

## Research Milestones



# Case-3 Plan (17 Run-Weeks in FY06 and FY07)

## Research Milestones



	FY05	FY06	FY07	FY08
Exp. Run-Weeks:	17	12 + 5*	12 + 5*	
<b>1) Transport &amp; Turbulence: Physical processes that govern heat, particle &amp; momentum confinement</b>	Characterize $q'$ & $\nabla T_e$ effects on electron transport	(2) Measure high-k turbulence	(2) Assess high-k turbulence spectra and electron transport	
<b>2) Macroscopic Stability: Role of magnetic structure on plasma pressure &amp; bootstrap current</b>	Study rotating plasmas close to "wall-stability" with EF correction	(3) Characterize effectiveness of closed-loop EF/RWM control	(3) Characterize tearing mode onset conditions & impact	
<b>3) Wave-Particle Interaction: Use of electromagnetic waves to sustain and control high-temperature plasmas</b>	Assess effects of beam-Alfvénic ion driven instabilities on core $J_{NB}$	(2) Characterize & optimize HHFW coupling	(3) Measure fast-ion transport due to fast-ion driven modes	
<b>4) Start-up, Ramp-up and Sustainment: Physical processes of magnetic flux generation and reconnection</b>		(2) Assess CHI creation of closed magnetic flux	(2) Test solenoid-free ramp-up	
<b>5) Boundary Physics: Interface between fusion plasmas and normal temperature surroundings</b>	Characterize pedestal and SOL of low-A, H-mode, high P/R plasmas	(3) Characterize Li pellet & evaporator coating effectiveness	(3) Assess long-pulse heat & particle control requirements of low-A, H-mode, high P/R plasmas	
<b>6) Physics Integration: Synergistic effects of external control and self-organization</b>	Characterize high-B/S & low-surface $V_L$ plasmas for $> \tau_{skin}$		(3) Characterize surface $V_L = 0$ plasmas for $> \tau_{skin}$	
		*CASE-3	(3) Advanced Particle Control Decision Point	